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Atomic ions which are stored in electromagnetic fields are an example of noneutral plasmas. Laser techniques allow control of plasma angular momentum and provide plasma cooling to temperatures much less than 1K. Using imaging techniques, plasma spatial information is achieved. Laser spectroscopic techniques allow measurement of plasma velocity distribution functions. Liquid and solid behavior of ion plasmas is studied.

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Summary of work on
"LIQUID AND SOLID ION PLASMAS"
(FY '89)

submitted to

Office of Naval Research

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ONR SUMMARY ON "LIQUID AND SOLID ION PLASMAS"

Introduction

In these experiments, performed at the National Institute of Standards and Technology, atomic ions are stored in combinations of electric and magnetic fields. The resulting nonneutral ion plasmas can be viewed as one component plasmas since global equilibrium is obtained over long times (many hours). The use of atomic ions allows the use of laser cooling, where the temperatures of the plasma can be reduced to 10 mK or less. For the densities typically achieved ($\simeq 10^8$ cm^{-3}) the plasmas become strongly coupled with coupling parameters Γ in excess of 100. The same lasers can be used to impart angular momentum to the plasma which provides a convenient method to control the density. The laser light which is scattered from the ions can also be observed in an imaging camera so the photographs and real time videos of the plasma can be made. Finally, by measuring the spectra of certain transitions in the ions, we can extract Doppler shifts and Doppler broadening which allows us to determine plasma temperature and rotation frequencies (and therefore, densities). Current efforts are devoted to applying these techniques to the measurement plasma dynamics and spatial correlations in ion plasmas.

Accomplishments in FY '89

This year has been largely devoted to a buildup phase for an apparatus which will be dedicated to ion plasma studies. Nevertheless, by sharing an apparatus which is also used for atomic ions spectroscopy experiments, we have been able to conduct some experiments briefly described below. Specific accomplishments are:

- Order superconducting magnet for dedicated studies. This magnet will have a maximum field strength of 4.5 T and a bore of about 5 in. which will allow images to be taken in a direction normal the Penning trap axis and resolve any spatial structure of the plasma. A new post-doc has started work in August '89; his efforts will be concentrated on bringing up this new apparatus.

- Observe cold thermal equilibrium plasmas for plasma rotation frequencies at or above conditions for Brillouin flow. By controlling the plasma angular momentum via laser scattering torque, we appear to be able to tune smoothly through the Brillouin condition.

- Developed technique for rapid measurement of plasma rotation frequency by the rotation induced frequency modulation of the ion electron microwave spin resonance.

- Observe quadrupole plasma mode by exciting the plasma with an electric field of quadrupole symmetry.

- Study the use of sympathetic cooling (i.e., cooling of one ion species by thermal contact with another laser cooled ion species) for long term confinement. Mg^+ ions have been used to cool Be^+ ions for periods of up to 20 hours.

Research Plans for FY '90

In general, we plan to follow the course of action outlined in our proposal of June, 1988. For the near term future we will concentrate on the following aspects of the work.

- Design and construct a Penning trap for use in the new superconducting magnet which has a promised delivery date of Feb. 1, '90. The new features which this apparatus will have over the old one are: (1) room to view the plasma in a direction normal to the magnetic field. This will allow us to investigate z-dependent spatial structure when the plasma is strongly coupled as has been predicted in some of the theoretical simulations, (2) A loading trap with hyperbolic electrodes in order to drive unwanted impurity ions out the trap, (3) Better vacuum to reduce the torque on the ion plasmas due to ion-neutral collisions. This is important when we try to go to very large numbers in search of infinite volume behavior.

- Build higher power U. V. laser source for cooling large samples of ions The hope is to see some evidence for infinite volume behavior in the existing apparatus but from recent measurements, it appears necessary to increase the available laser power. In all experiments to this date, laser powers have been less that 50 μW; by using external cavity buildup techniques, it should be possible to obtain powers greater than 1 mW.

- Investigate further the plasmas at the density corresponding to Brillouin flow. In this case, when viewed in the rotating frame, the plasma appears unmagnetized. Under these conditions, it may be possible to resolve whether our observed cylindrical shells under conditions of strong coupling are caused by the ions tending to follow magnetic field lines or are caused by some other effect.

- Investigate the use of stimulated Raman transitions to measure temperature in the ion plasmas. Previous temperature measurements rely on extracting the Doppler broadening contribution of the linewidth on allowed optical transitions. Unfortunately, at low temperature the width is dominated by the natural (radiative) width of the transition. This problem would be alleviated by driving stimulated Raman transitions and the measured linewidth would primarily be due to Doppler broadening.

Publications of the ion storage group in FY '89

Below are listed all of the research papers (not including abstracts) of the ion storage group at NIST published or submitted since the time the

proposal was written (June, '88). We feel this is appropriate since the work that is not specifically directed toward plasma studies has helped us to develop techniques which are useful in the plasma measurements. The papers which relate directly to plasma studies are denoted by an asterix.

A. PAPERS PUBLISHED IN REFEREED JOURNALS (since June 1, 1988)

1. "Precise Optical Spectroscopy with Ion Traps," W.M. Itano, J.C. Bergquist, R. G. Hulet, and D. J. Wineland, Physica Scripta T22, 79 (1988).

2. "Thermal Shifts of the Spectral Lines in the $^4F_{3/2}$ to $^4I_{11/2}$ Manifold of a Nd:YAG Laser," S. Z. Xing and J. C. Bergquist, IEEE J. Quant. Electronics 24, 1829 (1989).

*3. "Static Properties of a Nonneutral $^9Be^+$ Ion Plasma," L. R. Brewer, J. D. Prestage, J. J. Bollinger, W. M. Itano, D. J. Larson, and D. J. Wineland, Phys. Rev. A38, 859 (1988).

4. "Photon Antibunching and Sub-Poissonian Statistics from Quantum Jumps in One and Two Atoms," Wayne M. Itano, J. C. Bergquist, and D. J. Wineland, Phys. Rev. A38, 559 (1988).

*5. "Perpendicular Laser Cooling of Ion Plasmas in a Penning Trap," Wayne M. Itano, L. R. Brewer, D. J. Larson, and D. J. Wineland, Phys. Rev. A38, 5698 (1988).

*6. "Laser Cooling to the Zero Point Energy of Motion," F. Diedrich, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 62, 403 (1989).

7. "Rydberg Constant and Fundamental Atomic Physics," P. Zhao, W. Lichten, Z. Zhou, H. P. Layer and J. C. Bergquist, Phys. Rev. A39, 2888 (1989).

8. "Cooling in Traps," R. Blatt, G. Lafyatis, W. D. Phillips, S. Stenholm, and D. J. Wineland, Physica Scripta T22, 216 (1988).

9. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9Be^+$ Ground State," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert and D. J. Wineland, Phys. Rev. Lett. 63, 1031 (1989).

B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

1. "The Quantum Zeno Effect in a Two-Level System," W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, in preparation.

C. BOOKS (and sections thereof) PUBLISHED (Since June 1, 1988)

*1. "Liquid and Solid Ion Plasmas," D. J. Wineland, W. M. Itano, J. C. Bergquist, S. L. Gilbert, J. J. Bollinger, and F. Ascarrunz, In Non-neutral Plasma Physics, ed. by C. W. Roberson and C. F. Driscoll, A.I.P. Conf. Proc. 175, (American Institute of Physics, New York, 1988), p. 93.

*2. Trapped Ions and Laser Cooling II, ed. by D. J. Wineland, W. M. Itano, J. C. Bergquist, and J. J. Bollinger, NIST Technical Note 1324, 1988.

*3. "Ion Trapping Techniques: Laser Cooling and Sympathetic Cooling," J. J. Bollinger, L. R. Brewer, J. C. Bergquist, W. M. Itano, D. J. Larson, S. L. Gilbert, and D. J. Wineland, in Intense Positron Beams, ed. by E. H. Ottewitte and W. Kells (World Scientific, Singapore, 1988), p. 63.

4. "Frequency Standards in the Optical Spectrum," D. J. Wineland, J. C. Bergquist, W. M. Itano, F. Diedrich and C. S. Weimer, in The Hydrogen Atom, Ed. by G. F. Bassani, M. Inguscio, and T. W. Hänsch, (Springer Verlag, Berlin, Heidelberg, 1989) p. 123.

5. "High Accuracy Spectroscopy of Stored Ions," D. J. Wineland, W. M. Itano, J. C. Bergquist, J. J. Bollinger, S. L. Gilbert, and F. Diedrich, in Frequency Standards and Metrology, Proc. Fourth Symposium, Ancona, Italy, (Springer-Verlag, Berlin, Heidelberg, 1989) p. 71.

6. "Hg^+ Single Ion Spectroscopy," J. C. Bergquist, F. Diedrich, W. M. Itano, and D. J. Wineland, ibid, p. 287.

7. "Frequency Standards Utilizing Penning Traps," J. J. Bollinger, S. L. Gilbert, W. M. Itano, and D. J. Wineland, ibid, p. 319.

*8. "Quantative Study of Laser Cooling in a Penning Trap," W. M. Itano, L. R. Brewer, D. J. Larson, J. J. Bollinger, S. L. Gilbert and D. J. Wineland, ibid, p. 447.

*9. "Observation of Shell Structures with Ions Stored in Traps," J. J. Bollinger, S. L. Gilbert, and D. J. Wineland, Proc. of the Workshop on Crystalline Ion Beams, Wertheim, W. Germany, Ed. by R. W. Hasse, I. Hofmann, D. Liese (GSI report GSI-89-10, ISSN 0170-4546) p.231.

*10. "Coulomb Clusters of Ions in a Paul Trap," W. M. Itano, J. C. Bergquist, and D. J. Wineland, ibid, p. 241.

11. "The Digitized Atom and Optical Pumping," D. J. Wineland, W. M. Itano, J. C. Bergquist and R. G. Hulet, in Atomic Physics 11, ed. by S. Haroche, J. C. Gay, G. Grynberg, (World Scientific Press, Singapore, 1989) p. 741.

*12. "Liquid and Solid Phases of Laser Cooled Ions," S. L. Gilbert, J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland, ibid. p. 261.

D. BOOKS (and sections thereof) SUBMITTED

1. "Atomic Clocks," W. M. Itano, in McGraw-Hill Encyclopedia of Science and Technology, 7th Edition (McGraw-Hill), New York), (in press).

2. "Laser Cooling," D. J. Wineland, McGraw-Hill Encyclopedia of Science and Technology, to be published.

3. "Progress at NIST Towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano D. J. Heinzen, S. L. Gilbert, C. H. Manney, and C. S. Weimer, Proc. 43rd Annual Symposium on Frequency Control, Denver, June, 1989, to be published.

4. "Quantum Optics of Single, Trapped Ions," W. M. Itano, J. C. Bergquist, F. Diedrich, and D. J. Wineland, Proc. Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, NY, June, 1989, to be published.

5. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^{9}Be^{+}$ Ground State," D. J. Heinzen, J. J. Bollinger, W. M. Itano, S. L. Gilbert, and D. J. Wineland, ibid.

*6. "Observation of Correlations in Finite, Strongly Coupled Ion Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Proc. Yamada Conf. on Strongly Coupled Plasma Physics, Tokyo, Japan, Aug. 29-Sept. 2, 1989, ed. by S. Ichimaru.

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES (Since Oct. 1, 1988)

1. "Liquid and Solid Plasmas," Invited Review Taik at the Division of Plasma Physics meeting of the American Physical Society, Hollywood, FL, November 1988, S. L. Gilbert.
2. "Spectroscopy and Optical Frequency Standards with a Single Ion," Spring Meeting of American Physical Society, May 1-4 1989, Baltimore, J. C. Bergquist.
3. "Hg^+ Single Ion Spectroscopy," Ninth International Conference on Laser Spectroscopy, June 1989, Bretton Wood, NH, J. C. Bergquist.
4. "Optical Spectroscopy and Laser Cooling for a Single Ion," Gordon Conference on Atomic Physics, July 1989, Wolfeboro, NH, J. C. Bergquist.
5. "Observation of Shell Structure with Ions Stored in Traps," Workshop on Crystalline Ion Beams, Wertheim/Main, Germany October 1988, J. J. Bollinger.
6. "Observations of Correlations in Finite, Strongly Coupled Ion Plasmas," Yamada Conf. on Strongly Coupled Plasmas, Yamada, Japan, Aug. 1989, J. J. Bollinger.
7. "Coulomb Clusters of Ions in a Paul Trap," Workshop on Crystalline Ion Beams, Wertheim, W. Germany, Oct. 1988, W. M. Itano.
8. "Quantum Optics of Single, Trapped Ions," 6th Rochester Conference on Coherence and Quantum Optics, July 1989, W. M. Itano.
9. "Tests of Quantum Mechanics with Laser Cooled Ions," 5th Interdisciplinary Laser Science Conference, Stanford, CA, Aug. 1989, W. M. Itano.
10. "Laser Cooled Trapped Ions," (summer school, series of 5 talks) Univ. of Sao Paulo, San Carlos, Brazil, Jan. 1989, D. J. Wineland.
11. "Quantum Jumps, Ion Crystals and Solid Plasmas," Plenary talk at QELS, Baltimore, MD, April 1989, D. J. Wineland.
12. "Ion Frequency Standards, Progress at NIST," Frequency Control Symposium, Denver, CO, May 1989, D. J. Wineland.

F. OTHER INVITED TALKS (Colloquia etc.) (Since Oct. 1, 1988)

1. Physics Colloquium, the University of Michigan, Ann Arbor, Michigan January 1989, S. L. Gilbert.
2. Physics Colloquium, the University of Maryland, College Park, MD, January 1989, S. L. Gilbert.
3. Physics Colloquium, New York University, New York, NY, February 1989, S. L. Gilbert.
4. Physics Colloquium, the University of Notre Dame, Notre Dame, Indiana, October 1988, S. L. Gilbert.
5. Physics Colloquium, the University of Colorado, Boulder, Colorado, October 1988, S. L. Gilbert.
6. Physics Colloquium, the University of Southern California, Los Angeles, CA, March, 1989, S. L. Gilbert.
7. Physics Colloquium, UCLA, Los Angeles, CA, March 1989, S. L. Gilbert.
8. Physics Colloquium, MIT, Boston, MA, March, 1989, S. L. Gilbert.
9. Physics Colloquium, Auburn, Auburn, AL, March, 1989, S. L. Gilbert.
10. Physics Colloquium, Livermore Labs, Livermore, CA, January 1989, D. J. Heinzen.
11. Physics Colloquium, Univ. of Texas, Austin, TX, April 1989, D. J. Heinzen.
12. Physics Colloquium, Inst. of Physics, Mainz, W. Germany, October 1988, W. M. Itano.
13. Physics Colloquium, Los Alamos, Los Alamos, NM, October 1988, W. M. Itano.
14. Physics Colloquium, Utah State Univ. Logan, Utah, April 1989, W. M. Itano.
15. Physics Colloquium, Univ. of Chicago, Chicago, IL, October 1988, J. J. Bollinger.
16. Physics Colloquium, Notre Dame, September 1989, J. J. Bollinger
17. Physics Colloquium, U.C.S.D., LaJolla, CA, November 1988, J. J. Bollinger.
18. Physics Colloquium, Rice Univ., Houston, TX, November 1988, D. J. Wineland.
19. Physics Colloquium, Cornell Univ., Ithaca, NY, December 1988, D. J. Wineland.
20. Physics Colloquium, IBM, Yorktown Heights, NY, December 1988, D. J. Wineland.
21. Physics Colloquium, S.U.N.Y., Stony Brook, NY, December 1988, D. J. Wineland.
22. Physics Colloquium, Stanford Univ., Stanford, CA, February 1989, D. J. Wineland.